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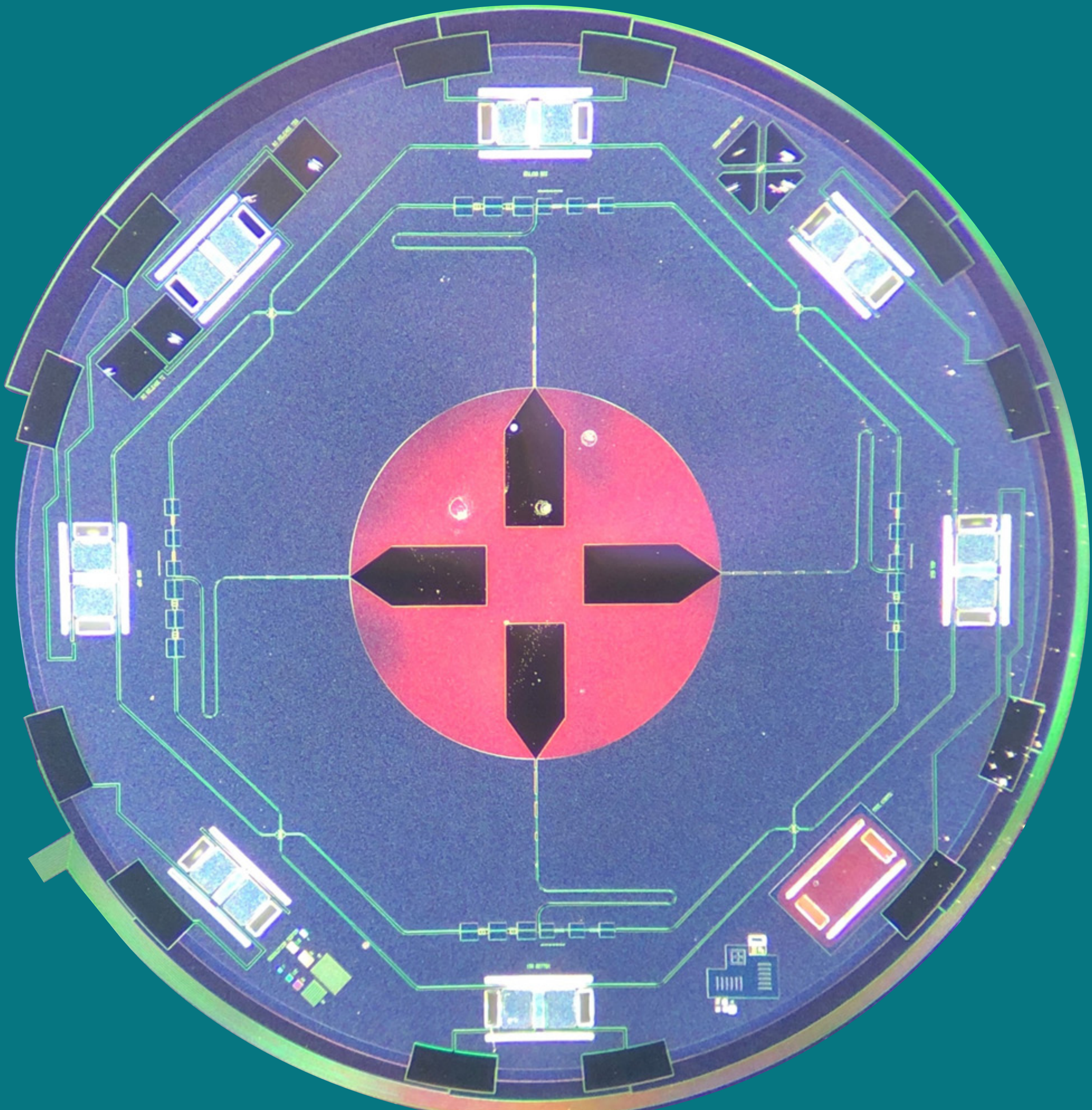
HIGH ENERGY PHYSICS (HEP) DETECTOR R&D PLAN

PHYSICS DIVISION

Lawrence Berkeley National Laboratory (Berkeley Lab) | 2021



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KA25 Detector R&D group

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INTRODUCTION

Berkeley Lab has a long history of innovation in detector instrumentation to drive discovery science in high energy physics (HEP) and cosmology. Once every decade or so a major new innovation has emerged at Berkeley Lab to enable new scientific advances. Examples include the pioneering low-background assay facility developed at Berkeley Lab in the 1960s, moved under the Oroville Dam in the 1980s, and then relocated to Sanford Underground Research Facility in 2015; the Time Projection Chamber (TPC) invented in the 1970s, now a workhorse not just for charged particle tracking at colliders but also for cryogenic noble liquid dark matter and neutrino experiments; the first ASICs for silicon vertex strip and pixel detectors, which were developed at Berkeley Lab in the 1980s and with successive generations continue to enable discovery at collider experiments; fully depleted charge-coupled devices (CCDs), which were first invented at Berkeley Lab in the late 1990s and are now in use on all Stage 3 and Stage 4 Dark Energy survey experiments, and with skipper readout architecture are also enabling low mass dark matter searches; the Berkeley Lab composites facility established in the 2000s which developed techniques that enabled large low mass detectors at LHC and RHIC; and more recently the development of cryogenic ASICs such as LArPix, LightPix and ColdADC which enable readout of neutrino events and related applications. In each case, unforeseen applications of the technology have proliferated. Going forward, these capabilities continue to evolve and remain highly relevant, while Microelectronics, Quantum Information Science and Machine Learning are emerging areas of intense development where today's investments may have important future impact.

Because detector R&D in the Physics Division at Berkeley Lab is driven by the goal of scientific discovery, priorities are established based on the potential for increasing sensitivity to new physics at existing, planned, or proposed DOE-HEP projects. The Lab presently has a strong involvement and continued interest in ATLAS/HL-LHC, DUNE, LZ, TESSERACT proposal, DESI and CMB-S4. New directions are also being pursued in Quantum Information Science (QIS) and Microelectronics.

Berkeley Lab is deeply involved in the Snowmass planning process leading up to the next P5 report, with seventeen leadership roles overall, including co-convening the Underground Facilities working group and one of the Liaisons between Underground Facilities and Instrumentation. We have co-authored twenty-five Snowmass Letters of Intent pertaining to future detector concepts; these are summarized by topic at the end of each section below, and the LOI details are provided in the Appendix.

Detector R&D through the lens of P5 Science Drivers and Priority Research Directions (PRDs)

DOE-HEP projects can be classified in terms of five Science Drivers identified by the Particle Physics Project Prioritization Panel (P5) in a 2014 report "Building for Discovery." The five Science Drivers guide the structure of the 2020 DOE Basic Research Needs (BRN) study on Detector R&D, which then delineates twenty-six Priority Research Directions (PRDs) in support of the Science Drivers.

Throughout this document, the current Berkeley Lab HEP Detector R&D Plan is summarized through the lens of those PRDs. The PRDs are organized into eight groupings in Table 1 of the 2020 BRN report (also reproduced here as **Table 1**). The detector R&D program at Berkeley focuses on six of the eight R&D areas: Nobles, Photodetection, Quantum, ASICs, Solid State and TDAQ, with several "X-cut" activities.

PRD: PRIORITY RESEARCH DIRECTION		
CALORIMETRY	**PRD 1:**	Enhance calorimetry energy resolution for precision electroweak mass and missing-energy measurements
	PRD 2:	Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments
	PRD 3:	Develop ultrafast media to improve background rejection in calorimeters and particle identification detectors
NOBLES	**PRD 4:**	Enhance and combine existing modalities to increase signal-to-noise and reconstruction fidelity
	PRD 5:	Develop new modalities for signal detection
	PRD 6:	Improve the understanding of detector microphysics and characterization
PHOTODETECTORS	**PRD 7:**	Extend wavelength range and develop new single-photon counters to enhance photodetector sensitivity
	PRD 8:	Advance high-density spectroscopy and polarimetry to extract all photon properties
	PRD 9:	Adapt photosensors for extreme environments
	PRD 10:	Design new devices and architectures to enable picosecond timing and event separation
	PRD 11:	Develop new optical coupling paradigms for enhanced or dynamic light collection
QUANTUM	**PRD 12:**	Advance quantum devices to meet and surpass the Standard Quantum Limit
	PRD 13:	Enable the use of quantum ensembles and sensor networks to fundamental physics
	PRD 14:	Advance the state of the art in low-threshold quantum calorimeters
	PRD 15:	Advance enabling technologies for quantum sensing
ASIC	**PRD 16:**	Develop process evaluation and modeling for ASICs in extreme environments
	PRD 17:	Create building blocks for Systems-on-Chip for extreme environments
SOLIDSTATE	**PRD 18:**	Develop high spatial resolution pixel detectors with precise high per-pixel time resolution to resolve individual interactions in high-collision-density environments
	PRD 19:	Adapt new materials and fabrication/integration techniques for particle tracking
	PRD 20:	Realize scalable, irreducible-mass trackers
TDAQ	**PRD 21:**	Achieve on-detector, real-time, continuous data processing and transmission to reach exascale
	PRD 22:	Develop technologies for autonomous detector systems
	PRD 23:	Develop timing distribution with picosecond synchronization
XCUT	**PRD 24:**	Manipulate detector media to enhance physics reach
	PRD 25:	Advance material purification and assay methods to increase sensitivity
	PRD 26:	Addressing challenges in scaling technologies

Table 1: The P5 Science Drivers and the corresponding R&D efforts (and associated PRDs).

The relationships between the P5 Science Drivers and Berkeley Lab R&D efforts are summarized in **Table 2,** which also indicates the relevant PRDs.

P5 SCIENCE DRIVERS	BERKELEY LAB R&D EFFORTS
Use Higgs Boson as a new Tool for Discovery	4D pixel chips in 28 nm CMOS (PRD 16–17, 18) Machine Learning in ASICs (PRD 16–17) LGAD sensors for Fast-timing (PRD 18) Ge pixel detectors (instead of Si) (PRD 19) 4D pixel chip DAQ (PRD 21) Wavelength domain multiplexed data links (PRD 21)
Pursue the physics associated with neutrino mass	LArPix: Liquid Ar TPC pixel readout (PRD 16–17) LightPix, modified LArPix for SiPM readout (PRD 16–17) Deep-cryogenic CMOS R&D (4K and below) (PRD 16–17)
Identify the new physics of dark matter	Maximize signal collection in liquid noble detectors (PRD 4) Signal characterization and Rn-tagging in crystalline Xe (PRD 4, 5, 6 and 25, 26) TESSERACT liquid helium dark matter detector (PRD 4, 5, 6) TESSERACT GaAs dark matter detector (PRD 4, 5, 6) Quantum evaporation from helium films (PRD 4) Noble liquid detector microphysics (PRD 6) Lower noise TES and MKID sensors (PRD 7) Skipper CCDs for dark matter searches (PRD 7) TESSERACT athermal phonon sensors (PRD 13) New materials for TES fabrication (PRD 13–14)
Understand cosmic acceleration: inflation and dark energy	Ge CCDs (PRD 7) Industrialization of CMB bolometer fabrication (PRD 8) Frequency multiplexing TES readout (PRD 13–14) New materials for TES fabrication (PRD 13–14) Fiber robots for beyond DESI (PRD 22 and 26)
Explore the unknown: new particles, interactions, physical principles	Ultimate low-threshold phonon sensors (PRD 13–14)

Table 2: The relationships between the P5 Science Drivers and Berkeley Lab R&D efforts.

NOBLES

Overview

Noble liquid R&D at Berkeley is focused on advancing dark matter detection techniques both for WIMP and for low-mass searches. The former targets improvements to liquid and crystalline xenon based experiments that could lead to cost-effective upgrades of the LZ experiment and is supported by an Early Career Award (Sorensen) and by KA25 funds, while the latter is focused on superfluid helium and solid state targets and is being carried out under the umbrella of the TESSERACT proposal (Transition Edge Sensors with Sub-Ev Resolution and Cryogenic Targets) with support from QuantISed, DMNI, a GIRA fellowship, and KA25 funding.

PRD 4, 5 and 6: Enhance and combine existing modalities to increase signal-to-noise and reconstruction fidelity; develop new modalities for signal detection; improve the understanding of detector microphysics and characterization

- **Maximize signal collection in liquid noble detectors.** We are studying correlation between PTFE type, preparation nd VUV reflectivity in LXe. Maximizing this reflectivity leads directly to maximizing the available scintillation signal. We are also planning to characterize VUV absorption of molecular impurities in LXe. These molecular impurities are understood to catalyze single electron and single photon noise in dual-phase xenon and argon TPCs.
- **Signal characterization and Rn-tagging in crystalline Xe.** CrystaLiZe R&D (**Fig. 1**) aims to characterize charge and light collection efficiency in crystalline xenon, with detection thresholds of a single quanta in each channel. Key measurements include the emission of electrons across the crystal/vapor interface, and possible recovery of the 15% of scintillation photons which are thought to be shifted deeper into the VUV in the crystalline state. This last measurement may be possible by using SiPM instead of traditional PMT. Finally, the project aims to demonstrate full tagging and thus mitigation of radon backgrounds. This could allow G2 dark matter search experiments to reach the neutrino floor.
- **TESSERACT liquid helium dark matter detector.** Part of the TESSERACT proposal, funded via Dark Matter New Initiatives (DMNI), intends to demonstrate background discrimination of electron recoils from nuclear recoils for sub-keV energy depositions in superfluid helium, by detecting scintillation photons and rotons (**Fig. 2**). This could position liquid helium as a key detection medium for low-mass dark matter. We recently acquired

Fig 1: Photo of the upgraded crystaLiZe TPC showing 16-element SiPM photosensor array, wire grid and Teflon walls.

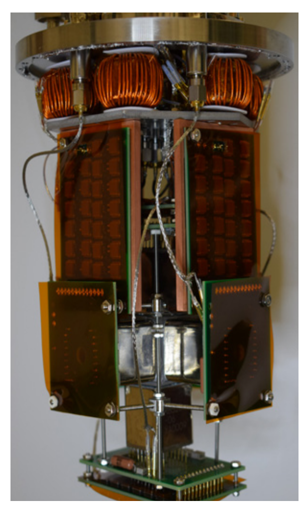

Fig 2: A liquid helium scintillation detector. Six photomultipliers are immersed in superfluid helium at 1.7 K, viewing scintillation light produced by scattering neutrons and gamma rays. Berkeley Lab is developing superfluid helium as a detector material for light dark matter detection.

a unique dataset of scintillation signals from both neutron and gamma scattering from superfluid helium, and preliminary analysis down to O(10) keV suggests agreement with theoretical models. This work has been partially supported by QIS and a GIRA fellowship. In FY21 we plan to calibrate both scintillation and quantum evaporation signals from superfluid helium with TES readout, so as to reach energies from O(10) keV down to O(100) eV. In subsequent years we intend to continue pushing the energy threshold down towards O(1) eV, in parallel with TES development. An end goal is particle identification from only rotons and phonons, via quantum evaporation.

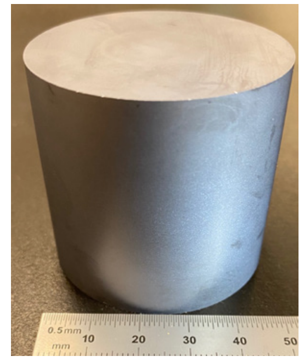

Fig 3: One of the brightest samples of silicon and boron-doped GaAs scintillator tested.

- **TESSERACT GaAs dark matter detector.** The TESSERACT project (**Fig. 3**) also intends to detect scintillation from GaAs using novel TES-based photodetectors (cf. PRD 7, 24). We have measured the luminosity of 27 GaAs samples (with an InGaAs phototube), unfiltered and with filters corresponding to the four emission bands at 850, 925, 1075, and 1350 nm. The samples are doped with different concentrations of silicon donors and boron acceptors and the luminosities vary from nearly zero to over 100 photons/keV. The radiative decay times range from 200 to 2000 ns. In FY21 and beyond we plan to characterize recently-ordered large kg scale samples using the TES-based photodetector. We also plan to study readout with large-area superconducting nanowire single photon detectors and microwave kinetic inductance (under development in our QuanTISED work).
- **Quantum evaporation from helium films.** An additional new modality for signal detection (part of TESSERACT) which we plan to study is the quantum evaporation of helium films from solid materials. Such materials include bright scintillators such as CsI and GaAs. The potential benefit is a means of measuring heat signals in those solid targets, without direct attachment of TES readout to the target.
- **Noble liquid detector microphysics.** We are developing a high-flux, 24 keV monoenergetic SbBe photoneutron beam for nuclear recoil calibration. Near-term applications are foreseen in characterizing liquid helium, liquid and crystalline xenon. We expect this neutron beam to be operational by 2022.

  We are developing a novel degraded alpha particle source to characterize the photon and electron response of condensed xenon to recoiling helium nuclei. This will provide key data to the proposed HydroX project (cf. PRD 24).

  We are planning to characterize the various signal channels in superfluid helium, including measurements of scintillation, triplet excimer, roton, phonon, and quantum turbulence.

Snowmass LOIs [1–2] (see Appendix).

PHOTODETECTORS

Overview

Berkeley is the birthplace of the fully-depleted CCD, now in wide use for cosmology surveys, as well as in low mass dark matter searches utilizing our skipper CCD readout design to achieve sub-electron noise. We are extending our CCD technology into Ge and developing new 200 mm wafer industrial fabrication partnerships. The second area of deep expertise in photodetectors at Berkeley is in the design and fabrication of Transition Edge Sensors (TES's), which are used for a variety of applications from mm wave detection in cosmic microwave background experiments to single photon detection for sub-Gev dark matter detection. We are also extending our expertise into Microwave Kinetic Induction Detectors (MKIDs) and Superconducting Nanowire Single Photon Detectors (SNSPDS). This research area is supported by an Early Career Award (Suzuki), SBIR, LDRD, US-Japan QuanTISED, and KA25 funds.

PRD 7: Extend wavelength range and develop new single-photon counters to enhance photodetector sensitivity

- **Lower noise TES and MKID sensors.** TES/MKID sensor development and characterization are key components of R&D for sub-GeV dark matter detection. We plan to implement this technology for photon detection across a wide range of frequencies. We also plan to characterize SNSPDs (obtained from JPL). If successful, it will offer an extremely low dark count rate (down to 10^{-4} Hz) photodetector, with sensitivity to presently challenging regimes of deep UV and near IR.
- **Skipper CCDs for dark matter searches.** SENSEI (**Fig. 4**) and the planned OSCURA experiment (both successors to the DAMIC experiment) intend to exploit the skipper CCD technology, and new proposals are forthcoming for astrophysics applications. Work is needed to improve the readout speed. Technology transfer to 200 mm fabrication (**Fig. 5**) at foundries, which is non-trivial for high-resistivity Si. We will also investigate methods (such as microwave annealing, molecular beam epitaxy and laser annealing) to achieve back-illumination of 200 mm wafer devices. This will require processing of 250 um thick wafers (a factor ~x3 thinner than standard foundry wafers) for astronomy applications, as well as to improve background rejection in dark matter detection experiments.

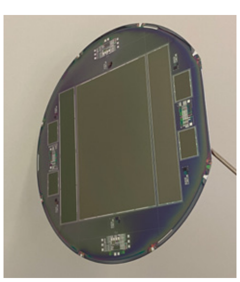

Fig 4: Picture of a 150 mm, Skipper CCD wafer from the DAMIC-M pre-production run.

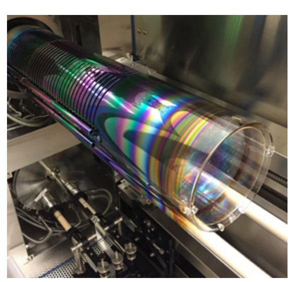

Fig 5: 150 mm wafers loaded into special "caged" quartz holders prior to a low pressure chemical vapor deposition step in the MSL.

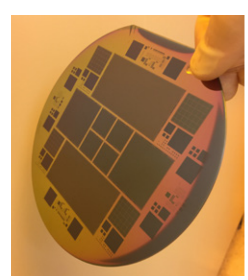

Fig 6: Partially processed, 150 mm Ge wafer.

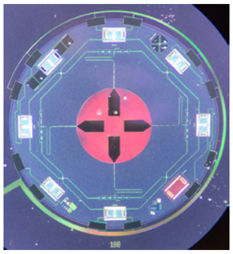

Fig 7: Photograph of the horn antenna coupled Transition Edge Sensor detector for Cosmic Microwave Background experiments fabricated commercially by Seeqc Inc.

Fig 8: Photograph of the silicon hemispherical lens with quartz anti-reflection coating. The lens is used for lenslet-antenna coupled detectors for Cosmic Microwave Background experiments.

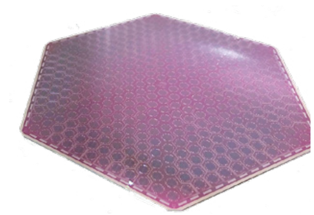

Fig 9: Photograph of the antenna coupled Transition Edge Sensor detector arrays for Cosmic Microwave Background experiments fabricated commercially by Seeqc Inc.

- **Ge CCDs.** We are developing Ge CCDs (**Fig. 6**) which would extend the wavelength cutoff from ~1 micron (Si) to ~1.5 microns (Ge). This would allow a larger volume of the Universe to be probed by follow-on experiments to e.g. DESI. We need to study and develop techniques for fabrication of the GeO_2 gate layer. We will also develop methods to reduce the dark current. Finally, we will investigate methods to process (novel) high-purity Ge substrates. Ge CCD's would also enable lower threshold DM searches.

PRD 8: Advanced high-density spectroscopy and polarimetry to extract all photon properties

- **Industrialization of CMB bolometer fabrication.** We are interested in growing collaborations to deploy new types of photon detectors that can enable single pixel spectroscopy, leveraging or ASIC capabilities.

  We plan to continue systematic industrialization of multichroic polarization-sensitive bolometer fabrication process steps for higher volume production at consistent quality with a focus on horn-coupled detector arrays (**Fig. 7**). In combination with previous work on lenslet-coupled detector arrays, (**Fig. 8**) this R&D will allow us to be ready for detector array production for CMB-S4 and other CMB experiments. This work is partially supported by SBIR in conjunction with SeeQC. At present we are focusing on two frequency bands per wafer (since CMB-S4 needs 7 total). This technology is capable of providing increased (order of magnitude more frequency bands) spectral resolution by changing the bandpass filter design.

Snowmass LOIs [3–7] (see Appendix).

QUANTUM

Overview

A major thrust of Berkeley Lab's QuantISED program is the development of advanced quantum sensors for phonon and microwave detection together with low noise, low power multiplexed readout to support large sensor networks. Additional support from DMNI and KA25 leverage this research area.

PRD 13: Enable the use of quantum ensembles and sensor networks for fundamental physics

- **TESSERACT athermal phonon sensors.** We are developing new, athermal phonon sensors and sensor arrays for the proposed TESSERACT experiment. These Transition Edge Sensors (TES) will have an energy threshold (i.e. energy resolution) better than 40 meV.

PRD 14 and 15: Advance the state of the art in low-threshold quantum calorimeters, and Advance enabling technologies for quantum sensing

- **Frequency multiplexing TES readout.** We are developing frequency multiplexing readout for TES sensors (**Fig. 9**). The goal of this work is to provide a lower-power, lower-heat, and lower-cost readout solution for experiments such as CMB-S4 which have a high TES channel count. It could also prove essential for TESSERACT and other low-mass DM experiments since these are expected to require approximately an order of magnitude more bandwidth for signal readout (cf. PRD 26).
- **New materials for TES fabrication.** We are also exploring different materials (**Fig. 10**) (in particular, Al-Mn) for CMB TES fabrication with tunable Tc. If the Tc can be tuned to a low enough value O(10) mK, it may be possible to apply this to dark matter search TES.
- **Ultimate low-threshold phonon sensors.** Develop ultimate low threshold phonon sensors, with the ultimate goal of reaching meV sensitivity. This is a broad program under QuanTISED with multiple outside collaborators. It involves both TES and KID based athermal phonon sensors, He quantum evaporation, electron emission, coherent spin sensors to detect both single electrons and single 3He atoms, SNSPDs to detect both phonons and quantum

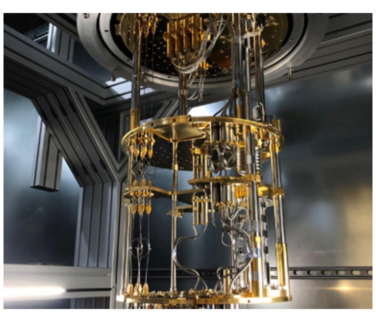

Fig 10: Photograph of dilution refrigerator cryostat used by Berkeley Lab physics division. The cryostat is installed in the shield room and the active anti-vibration crate.

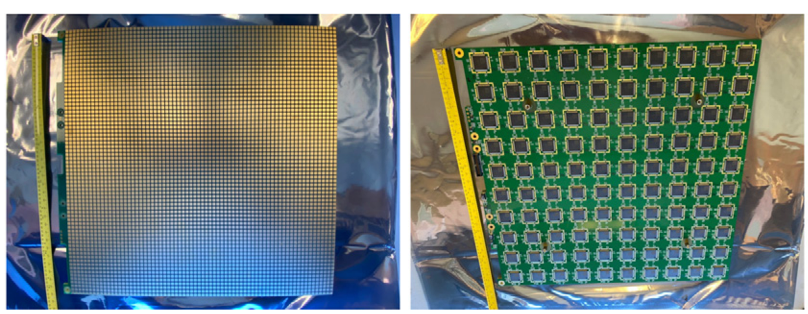

Fig 11: LArpix charge readout chip active side (left) and ASIC side (right).

evaporated He, optomechanical devices to detect ueV phonons in superfluid He, and Materials Science theory of phonon transport.

Snowmass LOIs [8–16] (see Appendix).

ASICs

Overview

ASIC design is a traditional Berkeley Lab strength which we have stewarded over many years, to ensure that we can support the evolving needs of the HEP program for compact, low-noise, low-power, radiation tolerant and cryogenic-compatible readout designs for use in experiments at the Energy, Intensity and Cosmic frontiers (**Fig. 12**). This work is supported by KA25, LDRD, an Early Career Award (Dwyer) as well as project support as designs mature and are translated into hardware for experiments (**Fig. 14**).

PRD 16 and 17: Evaluate process technology and develop models for ASICs in extreme environments, and Create building blocks for Systems-on-Chip for extreme environments

- **LArPix: Liquid Ar TPC pixel readout.** LArPix (**Fig. 11**) is evaluating 180 nm process technology and is leading toward a cold (77 K) standard cell library for that node. Further, we plan to build extreme-environment digital memory for this chip. LArPix is a 3D pixelated readout for LArTPCs such as the DUNE Near Detector, and aims to develop low-power large-area pixelated readout of LArTPCs with long term (> 30 yr) reliability. Pixelation has been demonstrated to provide superior event reconstruction and topological fidelity compared with projective wire readout. The LArPix-v2 chip has been produced (commercially) and tested at the 100k-channel level (20x pixel tiles, 5k pixels each), demonstrating viable commercial scalability of this technology. LArPix-v2 had demonstrated the system elements of Hydra I/O platform, a highly-configurable low-power fault-tolerant I/O technique for inaccessible readout systems. Future development is to incorporate ASIC clocking into the Hydra system to reduce risks of failure associated with clock distribution. Next steps include design and fabrication of instrumenting a mid-scale (~6.5 m^2 anode) prototype (ArgonCube 2x2 Demonstrator). In parallel, we will design, fabricate, and test a suite of standard 180 nm standard cells and prototype circuits tailored for longevity in cryogenic environments. We will execute a program of cryogenic accelerated aging tests of these components. In-house

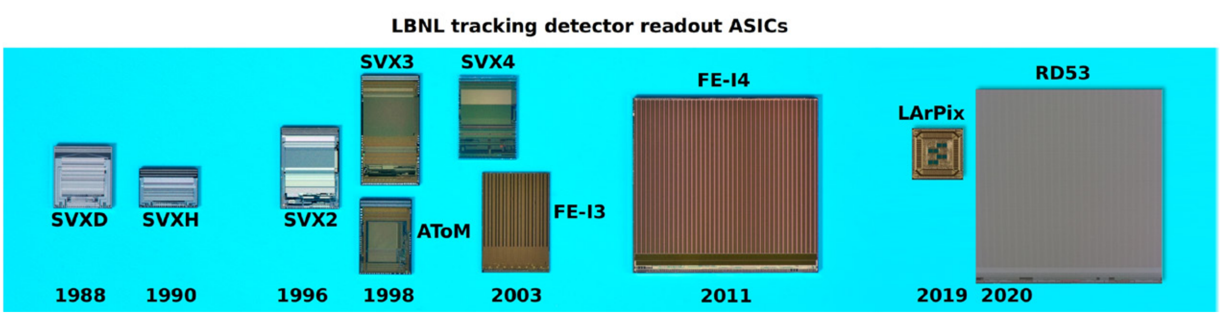

Fig 12: Berkeley Lab Tracking Detector readout ASICs designed and deployed over the past four decades.

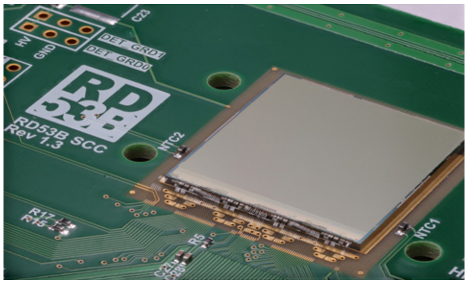

Fig 13: Picture of the ITkPixV1 pixel detector readout chip built in 65nm CMOS technology. Contains 153600 50umx50um pixels which can be read out at speeds up to 5.12Gbps.

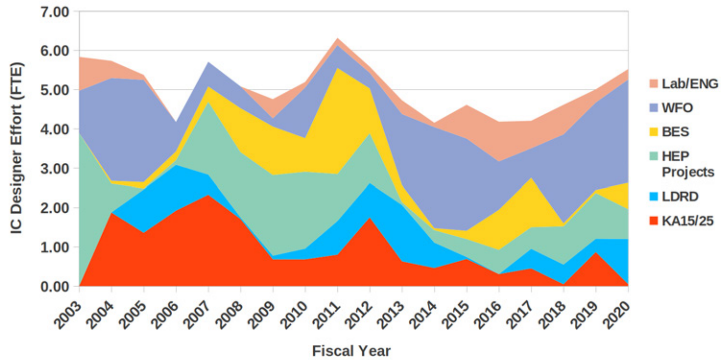

Fig 14: Historical Integrated Circuit designer funding profile and source.

device and circuit modeling capability is being developed and will be updated based on the outcome of these tests. The outcome from these developments will be incorporated into a future LArPix revision, meeting the reliability requirements for DUNE as well as other noble liquid detectors.

- **LightPix, modified LArPix for SiPM readout.** LightPix, a low-power and high-density SiPM readout chip, aims to provide scalable deployment of UV photon detection in a liquid argon environment (e.g. DUNE). SiPM coverage in many experiments is presently limited by the footprint of analog cables exiting the cryostat. A successful outcome would thus allow greater photon collection in a scalable package. It's basic building block is a modified LArPix chip. This work is proceeding with LDRD support.
- **Deep-cryogenic CMOS R&D (4K and below).** Our Deep-cryoCMOS R&D is evaluating 180 nm process technology in conjunction with custom simulation models for the deep cryogenic (4 K down to about 10 mK) environment. It aims to develop a scalable cryogenic amplifier, ADC and DAQ for NTD-Ge, TES and MKID sensors, with a goal of replacing existing HEMT and SQUID amplification. The immediate application to HEP would be multichannel TES readout in e.g. CMB-S4, directly with silicon amplifiers, without SQUIDs or analog multiplexing of signals. We expect this R&D to be applicable to fabrication of low-mass dark matter sensors. We are also investigating direct implementation of superconducting sensors (e.g. TES or SNSPD) on the same chip. Have made several test chips which can be compared with modeling. Going forward, we would like to make integrated deep cryo readout chips, a building block Amplifier, ADC and multiplexer macros for sub-4K operation with specific focus on ultra-low power I/O.
- **4D pixel chips in 28 nm CMOS.** The CERN RD53 collaboration was founded in 2013 following our early work no 65nm technology for pixel detector readout. We remain very active in RD53 (Garcia-Sciveres is co-spokesperson and Heim is testing coordinator) and are now following the example of our early 65nm work in the 28nm technology node.

  We are evaluating 28 nm process technology for a 4D pixel readout ASIC (**FIG. 12**). The end goal is a future upgrade to the 65 nm process ATLAS ITk Pixel detector (**Fig. 13**). The requirements include further miniaturization and the addition of precision timing capabilities (which makes "4D tracking"). We are designing a prototype with 50 um x 50 um pixel resolution and 100 ps timing precision (factor x4500 from 65 nm), high speed I/O and 1 GRad radiation tolerance (factor x2 from 65 nm).

- **Machine Learning in ASICs.** We plan to investigate the integration of machine learning (ML) in ASICs to process data from many pixels, and thereby improve position estimation. Collaborations are in formation but design work has not yet started. Personnel and funding limited (**Fig. 14**).

  We plan to carry out a proof of concept HEP prototype design using Artificial Intelligence (AI)-assisted CAD tools which are being developed at UC Berkeley and elsewhere under DARPA programs. Personnel and funding limited.

Snowmass LOIs [17–20] (see Appendix).

SOLID STATE

Overview

R&D at Berkeley Lab on solid state detectors is focused on pixel detectors with time resolution enabling 4D tracking, readout of LGAD fast timing detectors, and the use of Ge for pixel sensors in collider applications.

PRD 18: Develop high spatial resolution pixel detectors with precise high per-pixel time resolution to resolve individual interactions in high-collision-density environments

- **4D pixel chips in 28 nm CMOS.** Development of detector concept (starting with analog circuit and then proceeding to digital) using 28nm pixel readout ASIC designed for 4D tracking. We hope to submit a first chip design for fabrication later this year, with specifications as described above (cf. PRD 16).
- **LGAD sensors for Fast-timing.** Readout of low-gain avalanche detectors (LGAD) fast timing detectors. The integrated circuit development at Berkeley Lab can enable device and system testing of new LGAD sensors. Collaborative with UCSC.

PRD 19: Adapt new materials and fabrication/integration techniques for particle tracking

- **Ge pixel detectors (instead of Si).** We are interested in growing collaborations on new materials for particle detection, including SiC and Se, leveraging our readout ASIC capabilities

  We plan to investigate germanium instead of silicon pixel sensors using existing readout chips. Germanium pixel sensors can be produced as a spinoff of MSL Ge CCD development. Germanium sensors would be required eventually to go below 2–5micron pixel size, because at those sizes ionization statistics will degrade the position resolution of silicon.

Snowmass LOIs [21–23] (see Appendix).

TDAQ

Overview

Trigger and DAQ R&D at Berkeley Lab is focused on achieving higher throughput data streams for the pixel and tracking detectors we are developing.

PRD 21: Achieve on-detector real-time, continuous data processing and transmission to reach the exascale

- **4D pixel chip DAQ.** We are exploring means to readout 28nm process 4D pixel prototype chips — with data rates beyond the current 5.12Gbps — using online processing of data in Firmware and Software. This will be necessary due to advances in high precision timing information in addition to high spatial resolution.
- **Wavelength domain multiplexed data links.** We plan to develop Wavelength Domain Multiplexed (WDM), radiation hard optical readout to enable higher data output from tracking detectors. This is applicable to future HL-LHC inner layer upgrades enabled by 28nm readout chips. Collaboration with FNAL and Freedom Photonics.

PRD 22: Develop technologies for autonomous detector systems

- **Fiber robots for beyond DESI.** We are developing fiber robots (**Fig. 15**) for highly-multiplexed cosmology experiments. The current state-of-the-art are the DESI fiber robots that have a close-packed array of 5000 robots with a 10.4-mm spacing, positioning fiber optics with a requite accuracy of 5 microns. Next-generation cosmic experiments require smaller and more cost-effective designs, which we are developing and testing with university partners. Promising designs include ones based upon custom hollow-shaft brushless DC gearmotors, and ones based upon the smallest-available precision gearmotors. This work is supported by LDRD.

Snowmass LOIs [21–23] (see Appendix).

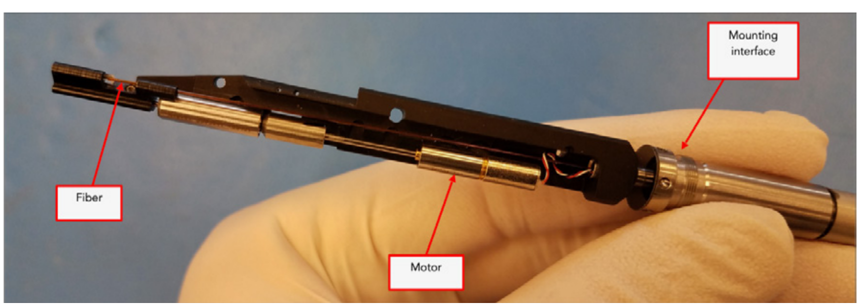

Fig 15: One DESI fiber robot positioner. 5000 such robots are packaged into the DESI focal plane with a 10.4 mm robot-to-robot spacing. Berkeley Lab is developing future robots that are packaged every 6.3 mm, while retaining a fiber positioning accuracy of a few microns.

CROSS-CUTTING (XCUT)

Overview

A number of the R&D directions described above are also part of the cross-cutting PRDs, as described below. We often find new applications that were previously unanticipated, so in that sense much of our detector R&D is inherently cross-cutting.

PRD 24: Manipulate detector media to enhance physics reach

- **TESSERACT GaAs dark matter detector.** We are exploring optimal doping of n-type GaAs with Si and B in order to maximize sensitivity to the hypothetical MeV-scale dark sector. Tuning the doping affects the dark count rate and the scintillation wavelength of the crystals.
- **Noble liquid detector microphysics.** We are planning a first calibration of the ionization and charge yields from He nuclei recoiling in liquid Xe, in support of the proposed HydroX upgrade to LZ.

PRD 25: Advance material purification and assay methods to increase sensitivity

- The Black Hills Underground Campus (BHUC) at Sanford Underground Research Facility (SURF) houses a world-class low-background screening facility which is operated by Berkeley Lab. As rare-event search experiments increase their sensitivity, their requirements for low-background detector construction materials also increase. We plan to develop lower background assay devices, calibration techniques for assays, and enhanced modeling and automated analysis technique. This work is not supported by KA25.
- **Signal characterization and Rn-tagging in crystalline Xe.** CrystaLiZe R&D offers a unique approach to effectively controlling the effect of U/Th radioisotope impurities in xenon TPCs by tagging their decays.

PRD 26: Addressing challenges in scaling technologies

- **Skipper CCDs for dark matter searches.** Future CCD production for the OSCURA dark matter search experiment (primary listing cf. PRD 7).
- **Industrialization of CMB bolometer fabrication.** Commercial superconducting detector and readout electronics fabrication (primary listing cf. PRD 8).
- **Frequency multiplexing TES readout.** Frequency multiplexing readout for TES sensors (primary listing cf. PRD 14–15).
- **Deep-cryogenic CMOS R&D (4K and below).** Deep Cryo-CMOS R&D (primary listing cf. PRD 16–17).
- **LArPix: Liquid Ar TPC pixel readout, LightPix, modified LArPix for SiPM readout.** LArPix and LightPix (primary listing cf. PRD 16–17).
- **Deep-cryogenic CMOS R&D (4K and below).** We are characterizing SiPM for detection of VUV scintillation, with an eye toward a future upgrade of e.g. the LZ experiment, in which replacing traditional PMTs with SiPM could lead to additional benefits. Examples include extended range of photon detection, compatibility with light element doping, increasing active target mass (by decreasing photosensor area) and lower radiogenic backgrounds (cf. PRD 4, 5, 7, 25).

- **TESSERACT liquid helium dark matter detector.** We are studying high voltage delivery in noble liquid/gas detectors (**Fig. 16**). The XeBrA test bed for LXe and LAr high voltage breakdown and electroluminescence studies is working to understand how breakdown probability scales with cathode area and liquid purity.
- In pursuing scaling technology, we have a strong track record of leveraging industry partnerships (e.g. through SBIR) to rapidly fabricate high-yield devices from R&D prototypes. Notable successes over the past decade include the composites lab, MSL, CMB detectors and ASICs work.

Snowmass LOIs [24–25] (see Appendix).

FACILITIES IN SUPPORT OF HEP

- Microsystems Lab (MSL), (**Fig. 17**).
  - Developing techniques and technology transfer for fabrication of CCDs for future cosmology and dark matter search experiments (cf. PRD 7, 8).
  - Developing techniques to fabricate high-yield LC resonators for separating a factor x10 more frequency bands in future CMB experiments (cf. PRD 8).
  - Developing CCDs (cf. PRD 7).
- The Integrated Circuits Group (Engineering Division) collaborates with the Physics Division on developing and designing new detector capabilities, as described in this report (see **Fig 12 on pg. 11**). While the IC group is leveraged by other projects, KA25 funding is critical to maintaining the innovative character of the group. Specific capabilities include:
  - IC testing on 8″ and 12″ wafer automated probe stations.
  - IC CAD tools.
- The Composites Facility was recently upgraded by Berkeley Lab with the addition of an additional structure to house a second large autoclave, (**Fig.18**) as well as HVAC upgrades. This facility is presently occupied building infrastructure for ATLAS, but R&D is ongoing with KA25 plus LDRD support to design new materials. We are uniquely capable of qualifying new resin systems for increased stability and radiation tolerance. These characteristics are

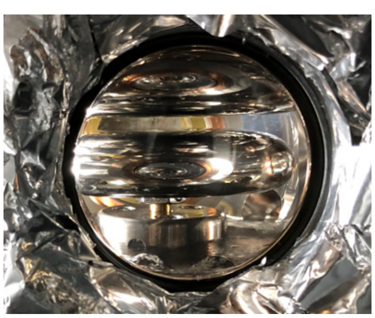

Fig 16: High-voltage electrodes immersed in liquid xenon. As liquid xenon detectors grow in size and improve their sensitivity to rare interactions, their high voltage requirements increase. R&D is underway at Berkeley Lab to understand, predict, and prevent dielectric breakdowns in liquid xenon.

Fig 17: Loading silicon wafers onto a SiC cantilever for an oxidation process.

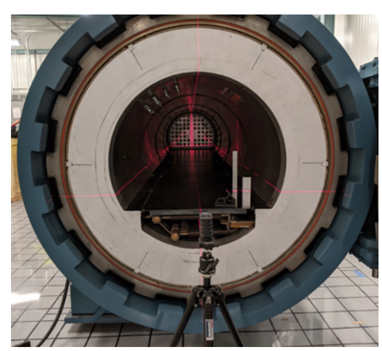

Fig 18: Autoclave shown with door open during levelling. The 3′X16′ cavity can achieve 34.5 bar and 454 C.

required for high-stability and low-mass detectors. A broad material survey for future detector construction needs to be started in the next 3–5 years. We have an extended process capability range (8 bar / 200 C typical, we can do 33 bar and 400 C) with the new autoclave which will be critical for this R&D.

- Other Facilities (not supported by KA25).
  - 88″ Cyclotron — provides ion beams to simulate space radiation for device testing, and a 55 MeV proton beam for up to 10 krad/hr for radiation hardness testing. It is also capable of producing short-lived nuclei for novel calibration applications.
  - Low Background Assay at SURF (cf. PRD 25).
  - Molecular Beam Epitaxy and Sensor Lab (Engineering Division) — Molecular Beam Epitaxy can produce ultra-thin metallic contacts, which enable extended UV and soft x-ray sensitivity for back-illuminated CCDs and other silicon sensors.
  - Molecular Foundry, an Berkeley Lab end-user facility which accepts proposals for fabrication of innovative new nano-materials.
  - UC Berkeley Marvell Nanolab — Berkeley Lab researchers have access to this facility for additional silicon processing tools and capabilities. Much of the CMB sensor technology described in this report began development in the Nanolab and its predecessor (the UC microlab, decommissioned in 2010).
  - UC Berkeley Wireless Research Center (BWRC) and Radio Astronomy Lab — offers Vector Network Analyzer tools which are useful to CMB detector development.
- We plan to collaborate with the Berkeley Lab Laser Accelerator (BELLA) center on development of electron test beams up to 10 GeV or more, powered by laser plasma acceleration. We are also considering development of multistage acceleration test beams. This would provide an opportunity to test a variety of HEP detectors, including those mentioned in this report (PRD 16, 17 and 21).
- We retain an interest in developing a local shallow underground facility for LHC R&D.

CLOSING REMARKS

The Berkeley Lab Physics Division maintains a broad portfolio of advanced detector R&D in support of High Energy Physics experiments. As described in this report, our efforts are well-aligned with the Priority Research Directions (PRDs) laid out in the Basic Research Needs (BRN) Report. The overarching goal of this R&D is to advance HEP detectors to new regimes of sensitivity, thereby continuing to enable new scientific discovery.

APPENDIX: SNOWMASS LOI

IF8 Noble Elements

[1] A crystalline future for dual phase xenon direct detection experiments (S.J. Haselschwardt, S. Kravitz, P. Sorensen, others). LOI #053

[2] R&D for low-threshold noble liquid detectors (P. Sorensen, many others). LOI #133

IF2 Photon Detectors

[3] Skipper CCDs for Cosmic Surveys of Dark Energy and Dark Matter (S. Holland, D. Schlegel, A. Drlica-Wagner PI (FNAL), others). LOI #021

[4] Status and plans for Oscura: A Multi-kilogram Skipper-CCD Array for Direct-Detection of Dark Matter (S. Holland, J. Estrada PI (FNAL), many others). LOI #080

[5] MegaMapper: a Massively-Multiplexed Spectroscopic Instrument for Cosmology (D. Schlegel, M. White, C. Poppet, S. Ferraro, others). LOI #090

[6] Charge-Coupled Device Technology Development for Future Dark Energy and Dark Matter Studies (S. Holland, D. Schlegel, others). LOI #133

[7] Cosmology and Dark Matter at a cm/s (B. Safdi, A. Kim, E. Linder, others). LOI #009

IF1 Quantum Sensors

[8] Operational definition of quantum sensors for HEP (M. Garcia-Sciveres). LOI #014

[9] A Scintillating n-type GaAs detector for sub-GeV Dark Matter Direct Detection (Edith Bourret-Courchesne, S. Derenzo, MGS, D. McKinsey). LOI #089

[10] The TESSERACT Dark Matter Project (SD, MGS, DNM, PS, AS, others). LOI #120

[11] Coupling Experiment and Simulation to Model Non-Equilibrium Quasiparticle Dynamics in Superconductors (AS, others). LOI #124

[12] Calorimetric readout of a superfluid 4He target mass (SD, MGS, DNM, PS, AS, others. LOI #158

[13] Tunable Quality Factor Resonators for High Energy Applications (A. Suzuki, others). LOI #167

[14] DMRadio-GUT: Probing GUT-scale QCD Axion Dark Matter (B. Safdi, others). LOI #219

[15] Hidden Orders in Quantum Matter and Dark Matter Detection (S. Griffin, others). LOI #170

[16] Quantum Sensing of 3He for Low-Mass Dark Matter Detection (T. Schenkel, others). LOI #055

IF7 Electronics/ASICS

[17] CMOS Deep Cryogenic Electronics for QIS and HEP (C. Grace, Anastasia Butko, M. Garcia-Sciveres, T. Heim, Y. Mei, Aikaterini Papadopolou, A. Suzuki, others). LOI #109

[18] Multiplexing Readout for next generation Dark Matter experiments with Transition Edge Sensors (A. Suzuki, Tucker Elleflot, others). LOI #145

[19] An R&D Collaboration for Scalable Pixelated Detector Systems (D. Dwyer, MGS, CG, A. Karcher, K.B. Luk, P. Madigan, B. Russell, S.R. Soleti, H. Steiner, others). LOI #171

[20] Monolithic Active Pixel Sensors for High Performance Tracking (Leo Greiner, Nicole Apadula, Alberto Collu, Ernst Sichtermann, others). LOI #160

IF3 Solid State Detectors and Tracking

[21] Wavelength Division Multiplexed high speed optical readout (M. Garcia-Sciveres, others). LOI #019

[22] Mu2e-II Tracker (D. Brown, others). LOI #094

[23] 28nm CMOS for 4D Tracker Readout Chips (T. Heim, K. Einsweiler, MGS, C. Grace, A. Krieger). LOI #104

IF9 Cross Cutting and Systems Integration

[24] Classification standard for underground research space (M. Garcia-Sciveres). LOI #001

[25] Linac to End Station A (LESA) as an Electron Test Beam (M. Garcia-Sciveres, others). LOI #045